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Status of the development of superconducting undulators at ANKA

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Abstract. In order to produce high-brilliance hard X-ray photon beams, permanent magnet short-period undulators are applied in many synchrotron facilities worldwide. Superconducting undulators (SCUs) have the potential to further increase the spectral range and brilliance. At the ANKA (Ångstrom source KARlsruhe) synchrotron radiation facility, we thus pursue an SCU-focused research and development program in a collaboration between the Karlsruhe Institute of Technology (KIT) and Babcock Noell GmbH (BNG), the status of which is reported in this contribution. The effort to develop instruments and tools for quality assessment of the magnetic field of SCUs and to enhance the understanding of beam heat load mechanisms in a cold bore is also described.

1. Introduction

For the production of synchrotron radiation with highest brilliance, third generation synchrotron sources make use of insertion devices (IDs). The state-of-the-art available for IDs today is based on permanent magnet technology, with magnet blocks placed inside the vacuum of the storage ring. Following an initial proposal at SPring-8 [1], the concept of Cryogenic Permanent Magnet Undulators (CPMU) evolved from in-vacuum undulators is presently considered for several synchrotron light sources. Superconducting undulators (SCUs) can reach, for the same gap and period length, higher fields even with respect to CPMU devices, allowing to increase the spectral range and brilliance [2].

At the ANKA (Ångstrom source KARlsruhe) synchrotron radiation facility, we pursue a research and development program for such superconducting IDs. The collaboration between ANKA and BNG (Babcock Noell GmbH) foresees the development of two planar devices, one of them with switchable period length.

2. A new superconducting undulator demonstrator for ANKA

A new SCU demonstrator to be tested at ANKA is currently under development [3]. The system is cooled by 4 cryocoolers that provide a total refrigerating power of 5 W at 4 K. The SCU demonstrator coils have a period length of 15 mm, with a total of 100.5 full periods plus an additional matching period at each end. The coils are fabricated using a commercially available NbTi superconductor. The operating magnetic gap is 8 mm, with a beam-stay-clear

(vacuum gap) of 7 mm. The beam vacuum chamber is quite challenging since, together with the requirements for a UHV radiation hard environment and the necessity to keep the resistive losses as low as possible [4], it needs to open to 16 mm during electron beam injection and energy ramping in the ANKA storage ring.

The field calculated from the Radia [5] simulations, using the pole height ($\pm 25\mu\text{m}$) and the half period length deviations ($\pm 5\mu\text{m}$) measured for the two coils at room temperature [3], has an r.m.s phase error of 5.6° over 186 poles [6]. Local field measurements of the 1.5 m long coils were performed in a liquid helium bath cryostat at CERN. The 1.5 m long coils reached 855 A/mm^2 [6] allowing to reach a peak field on axis at 8 mm magnetic gap of 0.69 T. The measured field shows, after mechanical shimming, an r.m.s. phase error of 7.4° on 106 poles, over a length of 0.795 m [6]. The expected flux at ANKA, calculated with B2E [7] from the measured shimmed field is higher than the one of an ideal CPMU, e.g., as designed for the Diamond Light Source (DLS) [8,9]. The use of mechanical shims to reduce the bimetallic effect, applicable to fixed gap undulators, together with further adjustment to keep the gap uniform to within $40\mu\text{m}$, would make it possible to reach an r.m.s phase error of $\sim 3.5^\circ$ without additional correction coils. For the installation of the SCU demonstrator at ANKA, where the gap is movable, BNG will prebend the coils at room temperature to try to compensate the bending measured at 4 K.

Because of the lack of a shimming technique for SCUs easily applicable to long devices ($> 1\text{ m}$) it is of course important to evaluate the real requirements on the r.m.s. phase errors for present and future applications. The flux calculated with B2E [7] by the field simulated with Radia taking into account the mechanical tolerances measured at room temperature and with an r.m.s phase error of 5.6° is reduced not more than 10% at the harmonics with respect to the one produced by the ideal field. This is demonstrated up to the 15th harmonic in the upper plot of Fig. 1. We can conclude that an r.m.s. phase error of $\sim 6^\circ$ is sufficient (flux reduction $< 25\%$) for the existing and planned storage rings up to the 15th harmonic [9].

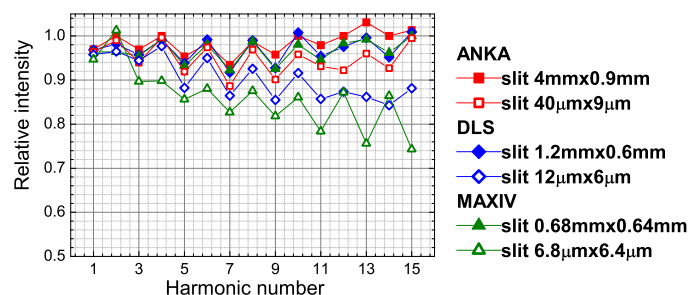


Figure 1. Ratio of the flux produced by the field simulated with Radia taking into account the mechanical tolerances measured at room temperature and with an r.m.s phase error of 5.6° , to the one from an ideal field at the different harmonics for ANKA, the DLS, and MAXIV [9].

3. Superconducting undulator wiggler

Switching between an 18 mm period undulator and a 54 mm period length wiggler is foreseen for the source of the planned IMAGE beamline at ANKA. At CASPERI (Characterisation Setup for Phase Error Reduction, see Sect. 5.1) [11] we demonstrated the feasibility of period length switching using a 9 pole mock-up designed and manufactured by BNG and showed that there is no need to train the magnet again after each switch [10].

In order to use only one power supply instead of two for the two circuits, thus reducing the thermal input to the device, work is ongoing at ANKA to develop a conduction-cooled superconducting switch (SCS). Conduction-cooled cryogen-free IDs as the ones under

development at ANKA make use of cryocoolers, which typically have a cooling power of 1-1.5 Watts at 4 K. For this reason, our application requires an SCS which must not dissipate more than a fraction of a Watt. A first successful test in an ad hoc conduction-cooled environment at CASPERI has been performed, demonstrating a minimum power dissipation of 200 mW per heater [12]. We believe that this value can be further reduced: additional tests are foreseen in the cryogen free environment in the facility CASPERII (see Sect. 5.1) [13].

4. New materials

The “work horse” wire material for superconducting magnets are multifilament NbTi wires, which today are also used for superconducting IDs. Even higher magnetic fields can be reached by using a conductor with enhanced critical current density, such as a NbTi wire with artificial pinning centers (APC), developed by SupraMagnetics, Inc. [14] and not yet commercially available. A racetrack coil has been built and measured to study the possible use of NbTi APC wire in SCUs [15].

Promising for future applications in SCUs are HTS (High Temperature Superconductor) tapes. Their engineering current density is rapidly increasing and they can be operated at higher temperatures than NbTi, allowing to sustain higher beam heat loads. HTS tapes can be used for planar SCUs in geometries similar to the ones used for NbTi wire. A short mock-up has been designed and manufactured by BNG [16] and tested in the facility CASPERI at ANKA/KIT, at 4 K reaching similar results as obtained with the new SCU demonstrator. Together with the group of W. Goldacker (Institute of Technical Physics, KIT) we follow at ANKA the proposal of S. Prestemon et al. [17] of an HTS tape stacked undulator for free electron lasers applications. The concept is particularly promising for narrow-gap, short period (< 10 mm) regimes. Still open issues in both the above described applications of HTS tape to SCUs are the quench detection and protection, radiation damage, engineering current density as a function of the magnetic field, stress and geometry, test field accuracy and the joint resistance of 50 – 100 nano-Ohm cm^2 [18]. This last point could be solved for a planar HTS SCU by using a winding scheme with no joints.

5. Tools and instruments for R&D

5.1. Magnetic field characterization

CASPER I is an operating vertical cryostat in which coils with maximum dimensions of 35 cm length and 30 cm diameter can be immersed in liquid helium for testing [11]. The magnetic field along the beam axis is measured by Hall probes fixed to a sledge and moved by a linear stage. The field and position precision are $\Delta B < 1$ mT and $\Delta z < 3\mu\text{m}$. With CASPER I, we can test new winding schemes, new superconducting materials and wires, and new field-correction techniques.

CASPER II is a horizontal cryogen-free test stand that will be used to perform quality certification (max. length 1500 mm, max. diameter 500 mm) of new superconducting IDs. It will also serve to test small prototype coils in a cryogen free environment. CASPER II is currently under construction. Quench tests performed with a 10-plate mock-up successfully confirmed its functionality, already demonstrated in the final acceptance test of the device [13]. In CASPER II, the magnetic field along the beam axis is measured by Hall probes fixed to a sledge and moved by a linear stage. The precisions are $\Delta B < 1$ mT and $\Delta z < 1\mu\text{m}$. Field integral measurements will be performed using the stretched wire technique.

5.2. Cold vacuum chamber for diagnostics

With the aim of measuring the beam heat load on a cold bore, needed to specify the cooling power for the cryogenic design of superconducting IDs, and in order to gain a deeper understanding in the beam heat load mechanisms, a cold vacuum chamber for diagnostics (COLDDIAG) was built [19]. We are offering its installation in different synchrotron light sources with

different energies and beam characteristics. COLDDIAG was installed in the storage ring at the Diamond Light Source in November 2011. With the equipped instrumentation, which includes temperature sensors, pressure gauges, mass spectrometers, as well as retarding field analyzers, it is possible to measure the beam heat load, total pressure, gas content, as well as the flux of electrons and/or ions hitting the chamber walls. Preliminary results show a superposition of linear and quadratic behavior of the beam heat load as a function of the average beam current. The measured beam heat load of 8.2 W at 250 mA is almost two orders of magnitude larger than the predicted value from resistive wall heating calculations (0.1-0.2 W, depending on the purity of the copper coating of the liner). The small, but visible effect of the solenoid on the temperature distribution points to electron bombardment as at least one component of the beam heat load observed. Currently, the design of the liner thermal transition is being optimized for further installation in a third-generation synchrotron facility [20].

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